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Theory Issues for Induced Plasma Convection Experiments in the Divertor of the MAST Spherical Tokamak

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Abstract

This paper surveys theory issues associated with inducing convective cells through divertor tile biasing in a tokamak to broaden the scrape-off layer (SOL). The theory is applied to the Mega-Ampere Spherical Tokamak (MAST), where such experiments are planned in the near future. Criteria are presented for achieving strong broadening and for exciting shear-flow turbulence in the SOL; these criteria are shown to be attainable in practice. It is also shown that the magnetic shear present in the vicinity of the X-point is likely to confine the potential perturbations to the divertor region below the X-point, leaving the part of the SOL that is in direct contact with the core plasma intact. The current created by the biasing and the associated heating power are found to be modest.

1 Introduction

In this paper, we discuss scrape-off layer (SOL) convection induced by electric biasing of the divertor tiles in a tokamak. This was suggested in refs. [1] and [2] as a means to increase the SOL thickness and thereby reduce the heat load on the divertor. Such experiments are planned on the Mega-Ampere Spherical Tokamak (MAST) at Culham [3]. For the conditions present in MAST and other tokamaks with a poloidal divertor, it may be possible to limit the zone where the convection is present to the divertor legs, which should minimize impact on the core plasma.

Electric biasing of the divertor tiles may not be the most practical approach to SOL broadening in a fusion reactor because of the possible degradation of insulators under intense neutron irradiation. On the other hand, the plasma physics effects related to this method of inducing the SOL convection are very similar to the corresponding effects in the other methods of inducing SOL convection (e.g., by toroidally asymmetric gas-puff, or by introducing toroidal waviness of the divertor floor [1, 2]). So the proposed MAST experiments should shed light on the prospects of these other methods, whose implementation in a reactor environment is more straightforward.

The basic theory of induced SOL convection was presented in refs. [1] and [2]. This paper surveys the concepts and summarizes further developments which enable straightforward application to an experiment, and in particular the one planned on MAST. More details of some of the calculations will be presented elsewhere [4]. Although our discussion is focused on MAST, most of the issues we discuss are not specific to this particular device and would be applicable to any tokamak; see for example our earlier reports [5, 6, 7], where the same issues were investigated for the COMPASS-D tokamak.

2 Overview of and parameters for MAST

MAST is a spherical tokamak that normally operates in a double-null magnetic configuration. We will be concerned with the outboard side of the plasma, where the proposed biasing experiment is to be carried out. (This is more practical in MAST than biasing the inner divertor.) The upper and the lower parts of this divertor are symmetric with respect to the horizontal mid-plane. Each divertor target consists of 12 radial carbon ribs (Fig. 1), which are 3 cm wide and 20 cm tall. They extend radially from $R = 100$ cm to $R = 166$ cm. Two of the ribs are wider than the others (19 cm instead of 3 cm); an array of flush-mounted Langmuir probes are situated on the upper surface of one of these two ribs, and thermocouples are installed on the other.

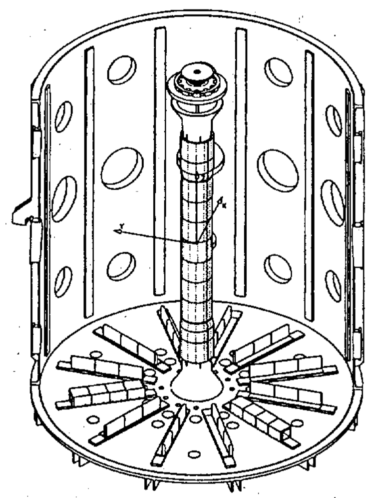

Fig. 1: sketch of MAST lower divertor, center post, and vacuum tank

The magnetic field in the plane containing the upper faces of the ribs is predominantly toroidal and intersects the surface of the upper faces at a shallow angle $\theta \sim 0.25$ rad, whereas the vertical surfaces are intersected almost normally (at $\theta \approx \pi/2$). The magnetic flux (and the plasma flow) is intercepted, therefore, mostly by vertical faces of the ribs. In the proposed experiment, every other rib (6 in total) of the lower divertor will be biased, while the rest of the ribs (6 in total) will remain grounded. The upper divertor will remain grounded. The maximum bias potential will be +100 V.

The divertor geometry and plasma parameters in the SOL vary depending on the tokamak operational regime. For numerical estimates, we choose the following set of parameters, which are representative of the present mode of operation. These parameters are "typical" ones, not necessarily met simultaneously in a particular shot. The toroidal and poloidal magnetic field strengths in the strike zone are, respectively, $B_T = 0.2$ T and $B_P = 0.04$ T. The vertical extent of the wetted area on each divertor rib is $a = 2\pi R B_p/12 B_T = 10$ cm. The radial width of the strike zone outside the separatrix is $b = 6$ cm; the same width is taken for the private flux region. The width of the main SOL (with no bias) is $b_0 \sim 1$ cm. The connection length between the lower X-point plane and the divertor surface for the field line that strikes the divertor at a distance $b = 6$ cm from the separatrix is $L_\parallel = 600$ cm. The plasma density at the divertor target is $n = 10^{12}$ cm^{-3}. The electron and ion temperatures are, respectively, $T_e = 10$ eV and $T_i = 60$ eV. (T_i is inferred from total power balance.) The above estimates imply ion and electron gyroradii $\rho_i = 0.5$ cm, $\rho_e = 0.003$ cm. We assume that the divertor operates in a low-recycling attached mode, so that the parameters of the plasma stream approaching the divertor are determined by sources situated above the X-point.

3 Bias required to produce significant broadening

We recall the naturally existing radial potential variation in the SOL. This variation is typically equal to $\Phi_1 \sim 3T_e/e$. The presence of this radial potential difference makes the equipotentials look as shown in Fig. 2 The electric drift moves plasma within an equipotential surface. Hence, for the case of bias which varies only toroidally, the bias required for significant broadening of the SOL is essentially just that the constant-potential surfaces distort by more than the SOL width: For a small biasing potential, the plasma flow is laminar, and displacement normal to the magnetic surface cannot exceed the amplitude of the wiggles of the equipotentials, $\delta r \sim b\Phi_0/\Phi_1$. This estimate holds for δr less than the SOL width b. On the other hand, for

$$\Phi_0 > \Phi_1 \tag{1}$$

the wiggles of the SOL exceed its initial thickness; this is the domain where a strong effect of the induced convection can be expected. Numerically, for the reference set of parameters listed in Sec. 2, condition (1) yields 30 V.

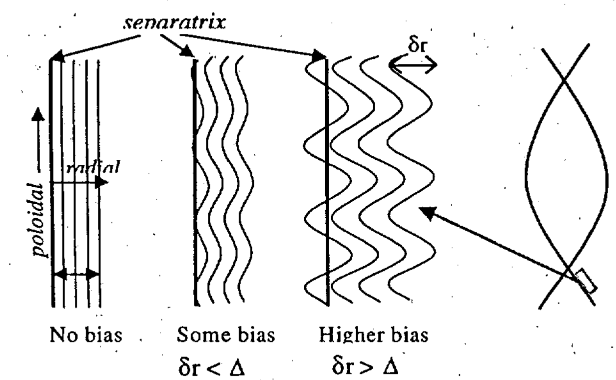

Fig. 2: Projection of the equipotentials on the poloidal cross-section of the SOL

As was pointed out in Ref. 1, one could reduce the required potential amplitude by segmenting the ribs in the radial direction, with bias applied to every second segment. The required potential difference decreases roughly in proportion to the number of radial segments. However, the ribs in MAST are not radially segmented; hence one has to use the constraint (1).

Note that the biasing will affect not only the common flux region but also the private flux region. It would be interesting to see if detectable signals are present at probes in the private flux region near the inner strike point.

4 Magnetic shear

In the vicinity of the X-point the magnetic field is strongly sheared. The shear causes each flux tube to be squeezed in one direction and to be elongated in the other direction, as noted in ref. [8]. As shown in ref. [8], for a model which linearly expands the magnetic field about the X point and a flux bundle which is initially rectangular below the X point, the elongation E varies exponentially with distance along a field line and linearly with the inverse of the poloidal distance y to the above-X-point separatrix (see fig. 3). The height of the wetted area of a rib a sets the basic vertical scale for potential variations near the ribs. A flux bundle of this height is squeezed by a factor $\sim (s/d)^{1/2}$ at the X-point plane, where s is the distance to the separatrix at the rib and d is the rib-to-X-point poloidal distance, and another similar factor an equal distance above the X-point plane. Hence, half-way out in the SOL of MAST where $s \sim 3$ cm (and $d = 70$ cm.), the $a = 10$ cm height of the wetted

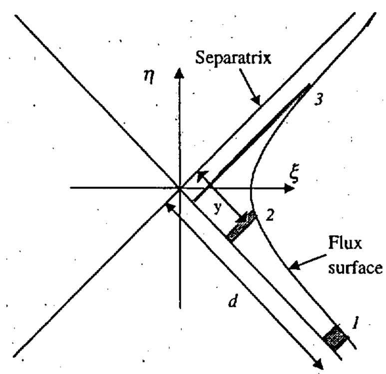

Fig. 3: Magnetic field in the vicinity of the X-point. 1, 2, 3 denote projections of the wetted surface of a divertor rib onto the poloidal plane at increasing toroidal distances.

area is mapped to 2 cm at the X-point plane. The height becomes less than the ion gyroradius 20 cm above the X-point plane. Hence we expect finite gyroradius effects to limit the potential perturbations primarily to the divertor leg.

5 Shear-flow turbulence

In the vicinity of the divertor plates, the potential variation occurs only in a narrow region at the interfaces of flux tubes leaning on biased and un-biased ribs. The potential gradients (and drift velocities) are very large in these zones, while they vanish in the rest of the flux tube volume. Such a state should, however, give rise to strong shear flow turbulence, which will smear out the flow over the whole flux tube and smooth the potential distribution.

We can estimate the width δ of the mixing region as a function of the bias potential Φ_b, or conversely the bias potential required to smooth over the entire image of a plate, as follows. The shear flow turbulence will be strongly flute-like in the divertor leg, with the flutes terminated on one end by the divertor plate (rib), and on the other end by the strong dissipation due to magnetic shear in the x-point region (as discussed in the preceding section), which we can model by a resistive endplate at the X-point plane. The shear flow turbulent layer thickness is limited by end-loss current (much as the standard SOL temperature width is limited by thermal endloss), and a consistency relationship from current continuity can be used to estimate δ. From the MHD momentum equation we can determine that $j_n = \mathbf{e}_n \cdot (c/B^2)\langle \mathbf{B} \times \nabla(m\widetilde{n\tilde{\mathbf{v}}}\tilde{\mathbf{v}})\rangle$ where $_n$ denotes normal to the shear flow layer. Using a standard renormalization approximation that $\mathbf{e}_n \cdot \langle \mathbf{B} \cdot \nabla(\widetilde{n\tilde{\mathbf{v}}}\tilde{\mathbf{v}})\rangle \approx \eta n dv_E/dx_n$ where η is the turbulent viscosity (momentum diffusivity) and v_E is the $\mathbf{E}\times\mathbf{B}$ speed, and estimating $d/dx_n = 1/\delta$, we can then estimate the turbulently driven normal current, integrated over the flux bundle that connects to a rib, to be $I_n \sim L_\parallel b\eta nmc^2\Phi_0/\delta^3 B^2$. For most wavelengths, end-loss does not appreciably modify the dispersion relation for the shear-flow instability from the unbounded case [4], and hence we expect $\eta \sim v_E\delta \sim c\Phi_0/B$ [9]. This must be balanced by the end-loss current resulting from the smoothed-out potential on one side of the sheath connecting to the step-like potential from biasing on the other; this current is $I_{\text{end}} \sim 2nec_s b\delta$ where c_s is the sound speed. Equating these currents gives our estimate,

$$\delta^2 \sim (c\phi_0/B)\left(L_\parallel/\omega_{ci}c_s\right)^{1/2} \quad . \tag{2}$$

In order for this flow to encompass the whole thickness of the flux tube (i.e., $\delta \sim a/2$), the following condition should be satisfied:

$$\frac{e\Phi_0}{T_e} > \frac{a^2[(T_e+T_i)/T_e]^{1/4}}{(8\rho_s^3 L_\parallel)^{1/2}} \quad , \tag{3}$$

where $\rho_s \equiv c_s/\omega_{ci}$. For our reference MAST parameters, this condition yields $\phi_0 > 400$ V, suggesting that turbulence would not spread over the entire flux tube. From the scaling in Eq. (2) we estimate that δ varies from $\sim 1/4$ to $1/2$ of the flux tube thickness a depending on bias potential. However, these estimates are approximate, and also finite-gyroradius effects should make the smoothing occur more rapidly. Note, the above treatment and results are different from the one described in ref. [4] (we will present details of these calculations elsewhere).

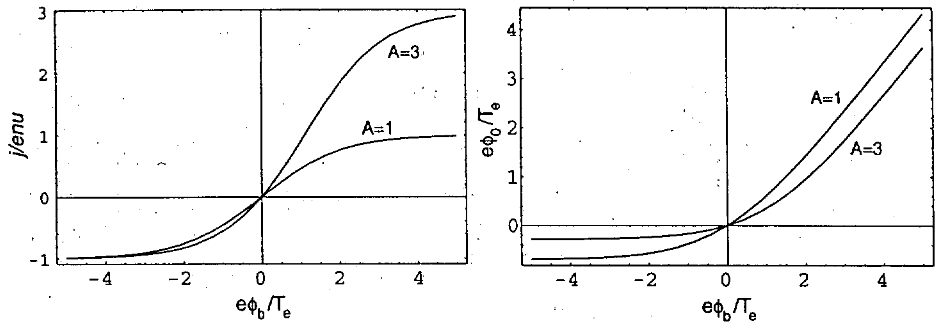

Fig. 4: Current density j and plasma potential Φ_0 vs biasing potential Φ_b

6 Effects of the sheath potential

The amplitude of the biasing potential used in the previous sections was Φ_0, the potential inside the plasma, not the actual potential Φ_b applied to the divertor ribs; they differ by the sheath potential. To evaluate this effect, we consider a flux tube that is in contact with a biased divertor plate at one end while the other end of the flux tube leans on a conducting plate that is kept at ground potential. This can be thought of as the upper divertor plate; one could also artificially introduce this grounded surface somewhere above the X-point, where the induced potential structures are most probably smeared out by the magnetic shear. We assume our flux tube has the same area at either end, and neglect potential variations along the flux tube outside the sheaths. Since the current flowing out through a sheath is $en\{-(v_{te}/2\pi^{1/2})\exp[-e(\Phi_0-\Phi_b)/T_e]+u\}$ where v_{te} is the electron thermal speed and u is the ion parallel flow velocity toward the plate, then, for the case of current following field lines, we can equate the current flowing out the grounded end to that flowing in the biased end to obtain two coupled equations for j, the current density from the biased end, and Φ_0. We can easily be more general and consider the case where the current does not strictly follow field lines so that the biased plates collect current from an area larger than their own area. In this case we equate the from the biased end to A times the current to the grounded end, with $A \geq 1$, to obtain the two coupled equations. The results are:

$$j = enuA\frac{\exp\left(\frac{e\Phi_b}{T_e}\right)-1}{\exp\left(\frac{e\Phi_b}{T_e}\right)+A}\quad , \Phi_0 = \frac{T_e}{e}\frac{\exp\left(\frac{e\Phi_b}{T_e}\right)+A}{A+1} \tag{4}$$

Plots of j and Φ_0 vs Φ_b are presented in Fig. 4 for various values of the parameter A.

From the plots we make the following observations: (1) The magnitude of Φ_0 is always less than that of Φ_b. For $A=1$, the difference is, however, insignificant at biasing potentials exceeding a few T_e/e. (2) By using negative biasing, it is impossible to create a potential modulation exceeding $0.8T_e/e$ inside the plasma. (3) For $A=1$, the current density does not exceed the ion saturation current even when operating at high positive biasing potentials. This is because the current at the grounded electrode is limited by the ion saturation current. For $A>1$ the current can exceed the ion saturation current, but only by the factor A which is at most 3 for the MAST experiment (since the ratio of grounded ribs at either end to the biased ribs is 3). A significant increase is possible only if the current collected by the biased ribs originates from large surface areas outside the SOL. This does not look very probable in light of experiments on TEXTOR [10] where positive biasing of the limiter (up to 500 V) was not accompanied by any significant increase of the current to it. This is important because, in order to reach potential variations inside a plasma exceeding a few times T_e/e, we need to introduce significant positive biasing: had the current density become too high, damage to the divertor ribs and power supply system would have been possible.

Similar calculations provide the heat flux to the divertor plates; it is, generally [11], $q = nu[W_i + e(\Phi_0 - \Phi_b) + 2T_e]$ where W_i is the ion energy lost per escaping ion. We can express the heat fluxes to the biased and grounded plates in terms of the (common) flux q^* in the case of no bias, to obtain:

$$q_{bias} - q^* = nuT_e \ln \frac{1 + \exp\left(-\frac{e\Phi_b}{T_e}\right)}{2} < 0 \tag{5}$$

$$q_{ground} - q^* = nuT_e \ln \frac{1 + \exp\left(\frac{e\Phi_b}{T_e}\right)}{2} > 0 \tag{6}$$

Somewhat paradoxically, the heat flux to the positively biased ribs decreases, whereas the grounded ribs experience an increased flux. For MAST, the predicted changes are modest; even for $e\Phi_b/T_e = 10$, corresponding to 100 V biasing voltage, one has $q_{top} - q^* \sim 0.5q^*$.

7 Discussion

We have developed a broad qualitative analysis of phenomena occuring during toroidally asymmetric biasing. Our treatment indicates that there should be a number of observable effects in the MAST biasing experiments. The plasma imprint on the divertor ribs in the lower divertor should be shifted alternately inward and outward or (if significant turbulence develops) broadened. The private flux region will be also affected. Excitation of the shear-flow turbulence is predicted, with characteristic frequencies $\omega \sim 4c\phi_0/Ba^2$ (for $\Phi_0 \sim 30$ V, $f \sim 40$ kHz). During positive biasing, the heat load on the unbiased ribs is predicted to increase. The induced shear flows may suppress, or least change the fluctuation spectrum of, pre-existing drift modes in the divertor leg. Strong biasing should not result in a current much larger than the ion saturation current, unless there is significant current being collected from the walls (as opposed to the divertor ribs). Measuring the limiting current will provide information about the degree to which current follows field lines and the likely source of current if it does not come from the opposite rib. The induced potential variations are predicted to be mostly confined to the divertor legs, implying that there should be little noticeable effect upon the core plasma.

Finally, we remark that the physics issues discussed in this paper are, for the most part, of quite general character, and hence our predictions, aside from the specific numbers, can be expected to apply to a variety of devices.

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